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Influence of climatic and geographic factors on the spatial distribution of Qinghai spruce forests in the dryland Qilian Mountains of Northwest China

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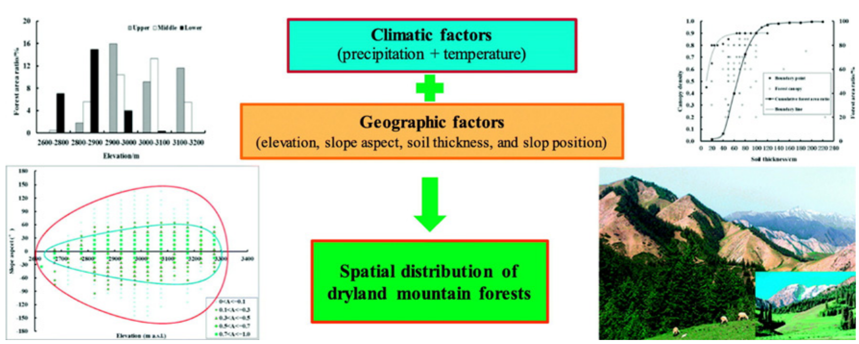
HIGHLIGHTS

- Both climatic and geographic factors affect the spatial distribution of Qinghai spruce forests in dryland high mountains.
- The potential forest distribution is determined by elevation and slope aspect.
- The actual forest distribution is further limited by soil thickness and slope position.
- Thresholds of annual air temperature and precipitation, slope aspect, soil thickness and slope position were determined.
- Considering climatic and geographic factors improves the prediction of forest distribution under changing environment.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of climate variables (temperature and precipitation) on forest spatial distribution is more prominent in dryland high mountains, where forest distribution is inherently very sensitive to and strongly limited by the substantial spatial heterogeneity of site conditions. Thus, a more reliable prediction of forest distribution under changing environment depends upon an understanding of the joint influence of climatic and topographic factors and their thresholds. This study was conducted on Qinghai spruce forests as dominant tree species in the Qilian Mountains of northwest China. The spruce forest distribution was surveyed by remote sensing in Dayekou watershed and by field investigation in a nested smaller watershed. Analyses showed that mean annual air temperature and precipitation, which vary with elevation, are the key climatic factors determining forest distribution, but slope aspect also plays an essential role. The potential core distribution area of denser forests and potential distribution area including sparse forests are between the axes of elevation (2635.5–3302.5 and 2603.4–3325.8 m a.s.l.) and slope aspect (−74.4–61.2° and −162.6–147.1° deviated from north). The corresponding threshold of mean annual air temperature at the upper elevation boundary is −2.59 and −2.73°C, while the threshold of mean annual precipitation at the lower elevation boundary is 378.1 and 372.3 mm, respectively.

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Using these thresholds and the elevation gradients of climatic factors, the shifting of elevation boundaries under climate change scenarios can be predicted. However, the forest distribution is also limited by a soil thickness of ≥40 cm; and by slope position of lower-, lower- and middle-, and entire-slope within the elevation ranges of <2800, 2800–2900, and >2900 m a.s.l., respectively. This study showed that adding geographic factors will greatly improve the prediction of changes in forest distribution area in dryland mountains, in addition to the influence of climatic factors.

1. Introduction

How to predict the response of spatial distribution of forests to climate change for making forest management more adaptive, is a global challenge we must face, since a growing number of studies suggest that climate change can affect the distribution of forests (McKenney et al., 2007; Williams et al., 2004; Zhou et al., 2001). Most studies have focused on the effects of annual temperature and precipitation, although the effects of increasing extreme weather events are also important. To assess the impact of projected future climatic change on the geographic distribution of forests and tree species, many studies have used interpolated baseline climate data to generate maps of current and future species distributions. Such studies have generally showed that tree species will expand or narrow their original distribution area (Klasner and Fagre, 2002; Yu et al., 2011). However, the response of forests distribution to climate change is more complex in mountains areas, especially in dryland regions, which cover one-third of the total land area of the world. In the mountain areas, there is a substantial spatial heterogeneity in environmental conditions, and the forest distribution is inherently very sensitive to and strongly limited by the great variation of site conditions, including precipitation (moisture), temperature, soil thickness and slope aspect. In order to cope with climate change, mountain forests will move into higher or lower elevations and change the main facing slope. Climate-driven upward migration of mountain forests has been demonstrated in a number of investigations (Lenoir et al., 2008; Shiyatov et al., 2007). The *Carpinion* forests (zonal vegetation of the present colline belt) will expand to areas that are occupied currently by sub-montane and low-montane *Fagus* forests if the annual mean air temperature increases by 2.2–2.75 °C on the Swiss Plateau (Brzeziecki et al., 1995). Analysis of the distribution of dense forests in the mountains of southern Siberia revealed that the total shift of preferred aspect of dense forests within the elevation range of 1800–2500 m above sea level (a.s.l.) was 120 ± 13° (Kharuk et al., 2010).

Situated in the northwest arid region of China and surrounded by desert and Gobi, the Qilian Mountains are named as the "humid island" and "water tower" of this arid region due to the relatively rich precipitation induced by the mountain terrain effect. The forests in the Qilian Mountains are important as a local timber source, but more important as the supplier of numerous ecosystem services, such as water regulation, soil erosion control, biodiversity protection, and carbon sequestration. Qinghai spruce (*Picea crassifolia*), as a tree species uniquely distributed in the Qilian Mountains and other neighboring dryland mountains in northwest China, is the dominant tree species accounting for 79.6% of the total forest area (Cheng et al., 2014) in the Qilian Mountains. While relatively rich studies have been done on the hydrological impacts of Qinghai spruce forests (Chang et al., 2014a; Chang et al., 2014b; Tian et al., 2011a), very few studies up until now have investigated the response of spruce forests spatial distribution to climate change. An exception was the single study of Xu et al. (2009a, 2009b) who used the maximum entropy model to simulate the potential distribution area of Qinghai spruce under current and projected future climate conditions, but without considering the impacts of geographic factors. He et al. (2013) reported that tree line elevations of Qinghai spruce have shifted upwards by 5.7–13.6 and 6.1–10.4 m in the periods 1907–1957 and 1957–1980, respectively, due to climate change in the Qilian Mountains. These published studies on the tree line response of Qinghai spruce to climate change did not evaluate the effect of the complex and non-uniform topography, which is generally characterized by basic topographic variables including elevation, slope aspect, slope gradient, soil thickness and slope position.

Studies on the response of spatial distribution of mountain forests to climate change are often constrained by a lack of adequate data for spatially depicting the variables, such as climatic parameters, due to the very sparse weather stations, steep terrain, harsh weather, and other reasons in many mountain areas. For example, in this study area, due to the existence of a long-term forest ecological research station, the first daily observational weather station was established in 1994 at an elevation of 2580 m a.s.l., while the second one was established in 1995 at an elevation of 2750 m a.s.l., but it only operated during the growing season (from May to October). Other weather stations at the higher elevations of 2900, 3000, and 3300 m a.s.l. were recently established but they were also only operated during the growing season.

This study was carried out at the watershed of Dayekou in the Qilian Mountains, where long-term ecological and hydrological studies of Qinghai spruce forests have been conducted, and where data on the spatial distribution of Qinghai spruce forests from both field investigations and remote sensing are available. The aim of this study is to assess the response of the spatial distribution of Qinghai spruce forests to both climatic and geographic factors. Specifically, we aimed firstly to determine the thresholds of annual air temperature and precipitation which directly determine the spatial distribution of Qinghai spruce forests (and their canopy density as an indicator of growth quality) by gathering and analyzing the forest distribution data from remote sensing, and the climate data from local weather stations. Secondly, we aimed to distinguish and quantify the limiting topographic factors using field investigation data. We intend that this research will enable us to more reliably predict the spatial distribution of Qinghai spruce forests, and therefore guide future forest restoration efforts in the mountainous areas of dryland regions under a changing environment.

2. Material and methods

2.1. Study area

The studied watershed of Dayekou, located between the latitudes of 38°25′N and 38°35′N and between the longitudes of 100°12′E and 100°19′E, is situated in the Qilian Mountains region of Gansu Province in northwest China (Fig. 1). Its total area is about 80 km^2 and the elevation varies from 2500 m to 3800 m a.s.l. A nested small watershed called Pailugou within the Dayekou watershed was also selected for this study. It is located at the central north edge of the Qilian Mountains (100° 17′E, 38° 32′N), close to Zhangye City, Gansu Province (Fig. 1). It has an area of 2.74 km^2 and an elevation range of 2642–3794 m a.s.l.

The Dayekou watershed has a temperate continental climate. While the atmospheric circulation in the cold and dry winter is controlled by the Mongolia anticyclone and with little precipitation; it is controlled by the continental cyclone in the summer. Based on the weather station located at an elevation of 2580 m a.s.l. (100°17′18″E, 38°34′03″N) and close to the outlet of Pailugou watershed, the mean annual precipitation

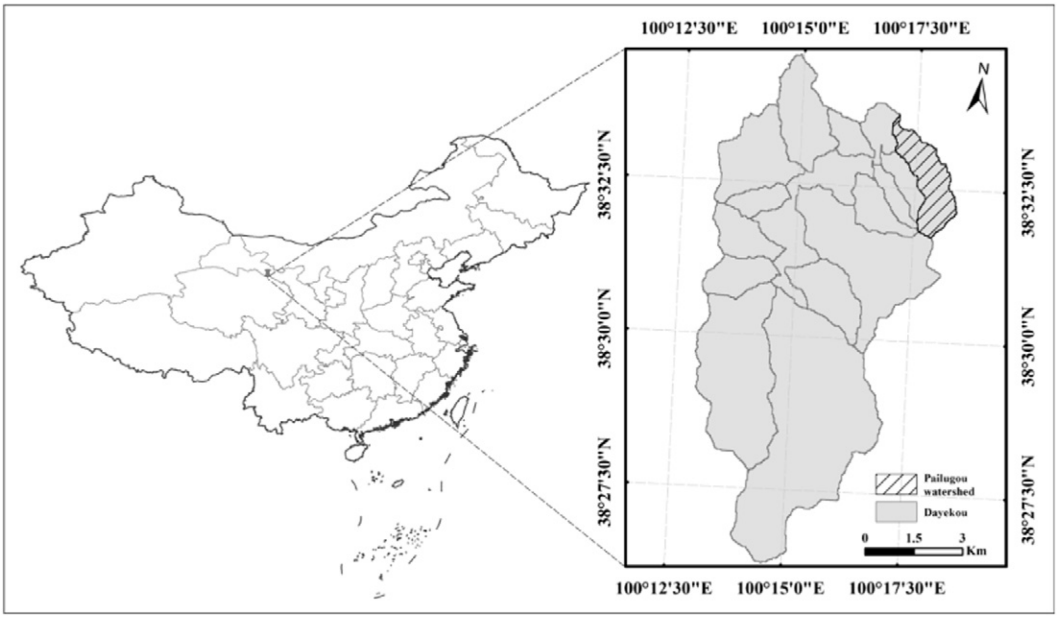

Fig. 1. Location of the watersheds of Dayekou and Pailugou in the Qilian Mountains of northwest China.

was 368 mm and the mean annual air temperature was 1.6 °C for the period 1994 to 2016 (Zhao et al., 2016). About 60% of the annual precipitation occurs in the summer period from July to September (Chang et al., 2014b). However, affected by mountainous climate, the temperature decreases and the precipitation increases with rising elevation, and this strongly influences the spatial distribution of forests and other vegetation. Permanently and seasonally frozen soils are widespread at the middle and higher elevation ranges in the small watershed. The main parent material is calcareous rock. The main soil type is gray soil, with a coarse texture, intermediate organic matter content, and a pH-value range of 7–8.

2.2. Collection of forest data by remote sensing

The forest coverage in the Dayekou watershed and the small watershed of Pailugou is 36.0% and 38.37%, respectively. These forests are mainly composed of two tree species, Qinghai spruce and Qilian juniper (*Sabina przewalskii*). However, pure stands of Qinghai spruce forests occupy about 95% of the total forest area, while the remaining forest area of Qilian juniper is concentrated on some sunny slopes with high elevation. From the remote sensing data it is difficult to distinguish the Qinghai spruce and Qilian juniper as accurately as field observations, so we ignore the existence of Qilian juniper in this study.

In June 2008, a remotely sensed campaign with an airborne LiDAR (LiteMapper 5600 system, Riegl LMS-Q560 scanner) and an onboard CCD (DigiCAM-H/22) camera were carried out over Dayekou watershed (Fig. 1). The flight height was about 800 m above the local topography, and imaging coverage was about 10 km × 6 km. With the wavelength of 1550 nm, a pulse of 3.5 ns at 50 kHz, the overall cloud point density of about 1.88 hits per square meter (thereafter low density) was acquired from this LiDAR system. The local Digital Elevation Model (DEM) and its derived data of topographic factors (i.e., elevation, slope aspect) and forest growth parameters (i.e., forest canopy, tree height), with 30 m resolution, from Tian et al. (2011b), were used in this study. According to the forest definition of the State Forestry Administration of China, only the vegetated points with a forest canopy density of ≥0.2 and a mean tree height of ≥5.0 m were considered as forests in this study.

2.3. Calculation of the relative forest coverage in Dayekou watershed

In order to show the spatial distribution of spruce forest more clearly than that shown with the massive and overlapping forested grids of remote sensing data, the Dayekou watershed dataset was divided into spatial cells. All the cells have an elevation range of 50 m and a slope aspect range of 10°, but with varying absolute area because of the varying slope gradient and the varying distance covered by a unit slope aspect with rising elevation. The number of forested grids in each spatial cell was counted; however, this number cannot be directly used for comparing the forest coverage of the cells, due to the varying absolute area of the cells. Moreover, the number of non-forested grids in each cell was not provided in the remote sensing data, so that we cannot calculate the forest coverage of each cell through dividing the number of forested grids by the total grid number. To solve this limitation, the following assumptions were made: 1) all the cells within the same elevation range have the same area (or quantity of grids); 2) within every elevation range (50 m) at least one fully (or very densely) forested cell exists and it can be adopted as the cell with the highest number of forested grids. Based on these assumptions, we divided the number of forested grids in each cell by the highest number of forested grids per cell within the same elevation range, to calculate the relative forest coverage (using this term is to distinguish it from the actual measured forest coverage) of each cell.

2.4. Collection of forest and site data by field investigation

To evaluate the effect of site factors on the spatial distribution of forests, the data collected by field investigation in the whole small watershed of Pailugou in 2003 were used. During this field investigation, the small watershed was divided into 342 spatial units, with the criteria of having the same or similar topography, vegetation type, soil properties and climate. The location of each unit was measured with a global positioning system (GPS), and its terrain characteristics (e.g., slope gradient, slope aspect, elevation) were recorded by a compass and an elevation meter. The soil thickness of each spatial unit was determined by the soil profile method. The forest canopy density, and the coverage of the shrub layer and grass layer were measured in each spatial unit by

the line transect method. The first step of the line transect method was to set up a line along the natural slope across the whole unit, and then record whether the points at certain intervals along the line transect were covered by trees, shrubs and grasses, by giving a coverage value of 1 if the coverage was ≥50%, or 0 if <50%. Finally, the coverage averages of all points in each spatial unit were calculated as the forest canopy density, or the coverage of the shrub and grass layer.

2.5. Collection of weather data and the estimation at any elevation within the watershed

Daily temperature and precipitation data from January 1, 1994 to September 30, 2015 in Dayekou watershed were obtained from the weather station near the outlet of the Pailugou watershed (100°17′18′′E, 38°34′03′′N, 2580 m a.s.l.). These data were used to calculate the mean annual air temperature and precipitation of the watershed at the elevation of 2580 m a.s.l. The data from this base weather station and other weather stations in the watershed at different higher elevations were used to derive the elevation gradient of annual air temperature and precipitation. The annual air temperature showed a decreasing rate of about −0.58 °C/100 m of elevation (Dong et al., 2007); while the mean annual precipitation showed an increasing rate of approximately 4.95% per 100 m of elevation (Chang et al., 2014b), as shown in the Eqs. (1) and (2) below.

$$P_a = 368^*(1+4.95\%)^{\frac{H_a-2580}{100}} \tag{1}$$

$$T_a = 1.6-0.58^*\frac{H_a-2580}{100} \tag{2}$$

where, P_a and T_a are the annual means of precipitation (mm) and air temperature (°C) at any elevation H_a (m a.s.l.) in the watershed of Dayekou. With these empirical equations, the thresholds of annual air temperature and precipitation determining the elevation boundary of the distribution area of spruce forests can be calculated based on the boundary elevation.

2.6. Valuation of site factors and classification of vegetation types in field investigation

In order to quantitatively analyze the impact of slope aspect on the spatial distribution of forests, the north-facing slope was valuated as 0°; whereas other slope aspects were valuated as their angle deviating from north. For example, the aspects of east and southeast were valuated clockwise as 90° and 135°; and the west and southwest were valuated in the counterclockwise as −90° and −135°. Moreover, the slope aspects were divided into shady (−45° to 45°), semi-shady (45° to 135°), semi-sunny (−45° to −135°) and sunny (135° to 180° and −135° to −180°) slopes.

In order to quantitatively analyze the impact of slope position on the spatial distribution of forests, all the slopes were divided into upper-slope, middle-slope and lower-slope. The slope position of each spatial unit was recorded as the position of its central point on the slope.

During the field investigation in the small watershed of Pailugou, each spatial unit was attributed visually to one of the following eight main vegetation types: forest, woodland, montane savanna shrubs, montane savanna grassland, shrubs, grassland, bare land and watercourse. Forest was defined as land with a tree canopy density of ≥0.2 and a mean tree height of ≥5.0 m; shrubs was defined as land dominated by shrubs without trees; and grassland was defined as land dominated by grasses without trees and shrubs, referring to the National Forest Inventory (NFI) Technical Regulations (2014) published by the State Forestry Administration of China.

2.7. Derivation of the effect of individual factor by boundary line approach

In nature, one variable can be influenced jointly by many other variables; this limits the analysis and derivation of the relation between one dependent variable and one independent variable from the non-controlled field data. To solve this problem, the boundary line approach (BLA) was developed and firstly described by Webb (1972). For doing this, the scatter plots are drawn between one dependent variable and each individual independent variable. The BLA is based on the hypothesis that the boundary line connecting the data points at the outer rim of the data body depicts the functional dependency to the observed independent variable which is supposed to be the only factor limiting the dependent variable. In this way, the effects of other independent variables portrayed by the points below the boundary line can be removed.

In this study, for deriving the effect of individual geographic factors on the spatial distribution of forests, scatter grams were plotted between the forest canopy density as the dependent variable and the site factors of soil thickness and slope gradient as independent variables. Each scatter gram contains 100 forested units selected from the field observations data set within the small watershed of Pailugou. The boundary data points were chosen for fitting a curve as the boundary line.

2.8. Statistical analyses

In this study, statistical analysis was carried out in Excel 2010. The fitting of the borderline of the potential forest distribution area was carried out in 1stOpt 1.5 (7D-Soft High Technology Inc., China). The boundary lines were fitted using SigmaPlot 12.5 (Systat Software Inc., USA). Remote sensing data processing used ArcGIS 10.3 (Environmental Systems Research Institute, USA), ENVI 5.3.1 (Exelis Visual Information Solutions, USA) and IDL 8.5 (International Telephone and Telegraph Corporation, USA).

3. Results

3.1. Spatial distribution of forests in Dayekou watershed

Using the mean elevation and slope aspect of each forested grid (with a forest canopy density ≥ 0.2 and a mean tree height ≥ 5.0 m) as the X axis and Y axis respectively, the spatial distribution pattern of Qinghai spruce forests in Dayekou watershed was plotted in Fig. 2. It can be seen that the forests are distributed within the elevation range of 2626–3306 m a.s.l., but mostly (accounting for 95%) within 2700–3201 m a.s.l.

Most forests exist on the shady slopes (−45° to 45°), where the soil moisture conditions are more favorable than on other slope aspects. At the lowest elevation range within the forest distribution area, the forested slope aspect range is narrow. However, as the precipitation increases with rising elevation, the range of forested slope aspect increases with rising elevation, until it reaches the maximum range (from −145.4° to 149.8°) at an elevation of about 3000 m a.s.l., then decreases gradually with increasing elevation. While 83.7% of the total forest area is concentrated on the shady slopes (−45° to 45°), the remaining 16.5% of forests grow on the semi-shady slopes (45° to 135°) and semi-sunny slopes (−45° to −135°), and rarely (only 0.2% of total forest area) on the sunny slopes (135° to 180°and −135° to −180°).

3.2. The borderline of potential distribution area of spruce forests in Dayekou watershed

The spatial distribution of Qinghai spruce forests with different relative forest coverage is shown in Fig. 3. The relative forest coverage of spatial cells on the sunny, semi-sunny and semi-shady slope is low, with 96.77% of cells lower than 0.3 and 70.97% lower than 0.1, i.e. the cells are mostly forested montane savanna. In contrast, the relative

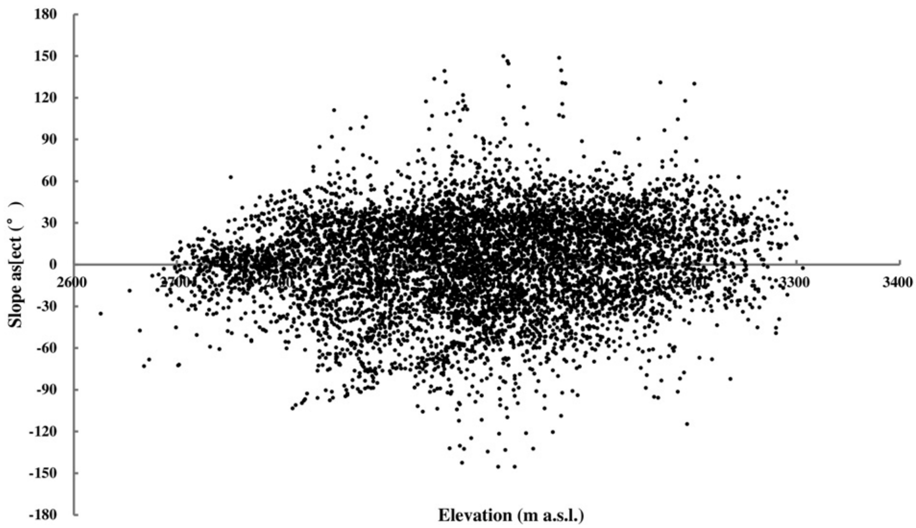

Fig. 2. The distribution of Qinghai spruce forests in relation to elevation and slope aspect in the Dayekou watershed (One point represents one forested grid, based on remote sensing data).

forest coverage of spatial cells on the shady slopes is high, with 80.0% of cells being >0.3.

After connecting the outlying points with relative forest coverage of >0 and >0.3 in Fig. 3, two borderlines are formed (Fig. 3). Within the inner borderline area, nearly all points with relative forest coverage of >0.3 were included. Therefore, we can assume it covers the potential core distribution area of Qinghai spruce forests in this watershed, if only considering the limitation of elevation (H, m a.s.l.) and slope aspect (A, °). The equation of the borderline of the core distribution area of Qinghai spruce forests was fitted as Eq. (3) below.

$$\frac{(H-3132.37)^2}{(-0.49^*H+1788.29)^2}+\frac{(A-6.61)^2}{67.78^2}=1 \tag{3}$$

According to this fitted borderline, the lower and upper elevation limits of the potential core distribution area of Qinghai spruce forests in the studied watershed are 2635.5 and 3302.5 m a.s.l., respectively. The slope aspect limits of the potential core distribution area of forests are −74.4° in the counterclockwise direction and 61.2° in the clockwise direction from north, respectively, at the elevation of 3132.4 m a.s.l. However, the limiting threshold of slope aspect varies with elevation, i.e., the suitable range of slope aspect is narrow at lower elevation, increases with rising elevation until reaching its largest value at the elevation of 3132.4 m a.s.l., then decreases sharply to 0° at the elevation of 3302.5 m a.s.l.

Within the outside borderline area, all forested points were included. This area can therefore be viewed as the potential distribution area of all spruce forests, both dense and sparse. The equation of this borderline was fitted as Eq. (4) below.

$$\frac{(H-3080.21)^2}{(-0.32^*H+1309.88)^2}+\frac{(A-7.73)^2}{154.82^2}=1 \tag{4}$$

According to this fitted borderline, the lower and upper elevation limits of the potential distribution area of spruce forests in the studied watershed are 2603.4 and 3325.8 m a.s.l., respectively. The slope aspect

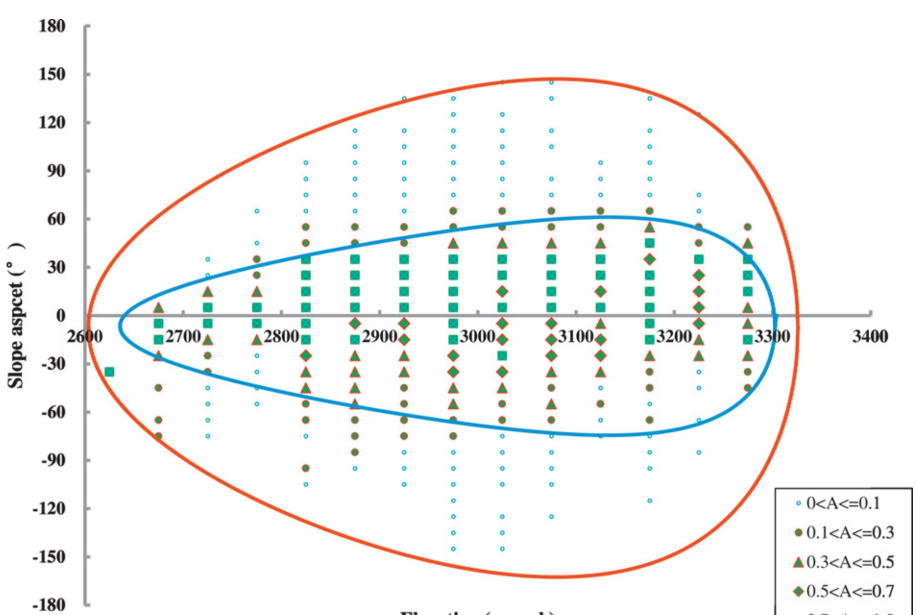

Fig. 3. The potential distribution area of Qinghai spruce forests and their relative forest coverage in spatial cells relative to elevation and slope aspect in the Dayekou watershed (A: relative forest coverage).

limits of the potential distribution area of spruce forests are −162.6° in the counterclockwise direction and 147.1° in the clockwise direction from north, respectively, at the elevation of 3080.2 m a.s.l., where the largest range of slope aspect of spruce forest distribution exists.

3.3. Thresholds of climatic factors of the potential distribution area of Qinghai spruce forests

The climate factors have a strong impact on the spatial distribution of forests. It was accepted that temperature and precipitation are generally the key influencing factors. Therefore, we selected the mean annual air temperature (T_a) and mean annual precipitation (P_a) to determine the spatial distribution of Qinghai spruce forests in Dayekou watershed.

According to observation data at the base weather station in the Dayekou watershed, the mean annual air temperature is 1.6 °C and the mean annual precipitation is 368 mm at the elevation of 2580 m a.s.l. Eqs. (1) and (2) were used to describe the change of annual air temperature and precipitation along the elevation gradient in the studied watershed.

The corresponding climatic factors at the upper and lower border elevation of the distribution areas of Qinghai spruce forests were calculated (Table 1). The limiting thresholds of T_a at the upper elevation border of the potential and potential core distribution areas for Qinghai spruce forests are −2.73 and −2.59 °C, respectively. The minimum annual precipitation at the bottom elevation border for the potential and potential core distribution areas of Qinghai spruce forests are 372.3 and 378.1 mm, respectively.

3.4. Geographic factors limiting the existence of forests within the potential distribution area

It can be seen from Fig. 3 that many spatial cells without forests exist within the potential distribution area of Qinghai spruce forests in the Dayekou watershed, indicating that other geographic factors besides elevation and slope aspect also play a role in limiting the existence of spruce forests. To figure out the causes of this phenomenon, we analyzed the field inventory data sets at the small watershed of Pailugou, where vegetation and site characteristics in all spatial units (both forested and non-forested units) were investigated. This allows us to detect the important geographic factors limiting the spatial distribution of Qinghai spruce forests.

The spruce forests in Pailugou watershed occupied a wide soil thickness range of 10–225 cm (Fig. 4). However, the forested units with a soil thickness <40 cm account for only 6.23% of the total, i.e., 93.77% of forest units have a soil thickness ≥40 cm. According to the fitted boundary line describing the variation of canopy density of Qinghai spruce forests with soil thickness, the canopy density increases quickly from about 0.5 to 0.8 when the soil thickness increases from 10 cm to 30 cm, then it increases slowly and reaches 0.87 at the soil thickness of 40 cm, and thereafter it remains nearly stable to approach its maximum of 0.9. Among the forested units with a soil thickness <40 cm, 55.56% are located at lower elevation ranges (2600–2900 m a.s.l.), shady slope and middle or lower slope positions, which means that these forests may live at least partly on extra water input (except precipitation) in the form of runoff from upslope. However, the forests with a soil thickness <40 cm do not grow well, as indicated by their lower canopy density. Based on this analysis, a threshold of soil thickness of ≥40 cm can be derived for judging the site suitability for forest growth.

Table 1
Thresholds of climatic factors for the distribution of Qinghai spruce forests in Dayekou watershed.

Area	Boundary	Elevation/m a.s.l.	Mean annual air temperature/°C	Mean annual precipitation/mm
Potential distribution	Upper	3325.8	**−2.73**	527.8
	Lower	2603.4	1.46	**372.3**
Potential core distribution	Upper	3302.5	**−2.59**	521.8
	Lower	2635.5	1.28	**378.1**

Compared with the large range (8–46°) of slope gradient that Qinghai spruce forests occupied in Pailugou (Fig. 5), the boundary line of canopy density of Qinghai spruce forests showed a very narrow variation range with slope gradient. The decreases of canopy density with rising slope gradient in the range of >25° is easily understandable; but, its decrease with lowering slope gradient in the range of <25° should be best explained by the disturbance of other land uses, such as timber harvesting before the 1980s, and grazing. This has resulted in a very low area ratio of 8.27% of Qinghai spruce forests growing on gentle slopes (<15°), while 56.65% grow on steep slopes (>30°). This fact indicates that slope gradient plays a minor role in determining the spruce forest distribution.

It can be seen from Fig. 6 that at the elevation range of <2800 m a.s.l. (as there is only one Qinghai spruce forest unit below 2700 m a.s.l., this elevation range was merged into the elevation range of 2600–2800 m a.s.l.), the spruce forests are mainly distributed on the lower-slopes. Within the elevation range of 2800–2900 m a.s.l., the spruce forests are mainly distributed at the lower- and middle-slopes, accounting for 5.55% and 14.93% of the total spruce forest area in Pailugou watershed, and forests begin to occupy the upper slope position. At the elevation range of >2900 m a.s.l, the spruce forests are distributed throughout the entire slope, and the forests growing on upper slopes account for 36.69% of the total forest area in the watershed.

4. Discussion

4.1. Temperature and precipitation change in the Qilian Mountains

The global land surface was warmed at a mean rate of 0.08–0.14 °C per decade from 1951 to 2012. However, the warming rate in China and the dry northwestern China was much higher than the global average. A linear increase of 0.23 °C per decade for China's surface temperature from 1951 to 2009 has been reported, and an increase of annual mean air temperature of 0.6 °C per decade since 1980 in northwest China (Zhao et al., 2011). The mountainous areas in arid regions are much more sensitive to climate change. The climate warming rate at higher altitudes in the Qilian Mountains was much faster than the above reported global average and China's average, with an increase in mean annual air temperature of 1.25 °C from 1980 to 2007 (Gao, 2015), corresponding to an increase rate of 0.45 °C per decade.

Under the changing climate, the precipitation amount and distribution pattern have varied greatly among different regions of the world. In many regions, climate change means a change to a warmer and drier climate. For example, there has been a long-term drying trend in Syria combined with the long-term warming trend in the Eastern Mediterranean (Kelley et al., 2015), a drying trend in northern Amazonia since the mid-1970s with a warming rate of 0.25 °C per decade (Malhi et al., 2008), and reduced precipitation associated with warmer temperatures in California (Swain et al., 2014). However, previous studies have shown that the climate in northwest China has experienced a warm-dry to warm-wet transition since the 1980s (Shi et al., 2007). Yin et al. (2009) have reported an annual precipitation increase rate of 1.355 mm per year from 1956 to 2005 in the Qilian Mountains. This is likely dependent on the melt of snow/ice pack, as the glaciers in the Qilian Mountains have shrunk by 20.88% within half a century since 1956 (Sun et al., 2015).

4.2. Influence of climatic factors on the elevation boundary of spruce forest distribution

The distribution of mountain forests in arid regions is undoubtedly affected by many climatic factors, e.g. temperature, precipitation, solar radiation, and so on (Grubb and Whitmore, 1966). Among them, the

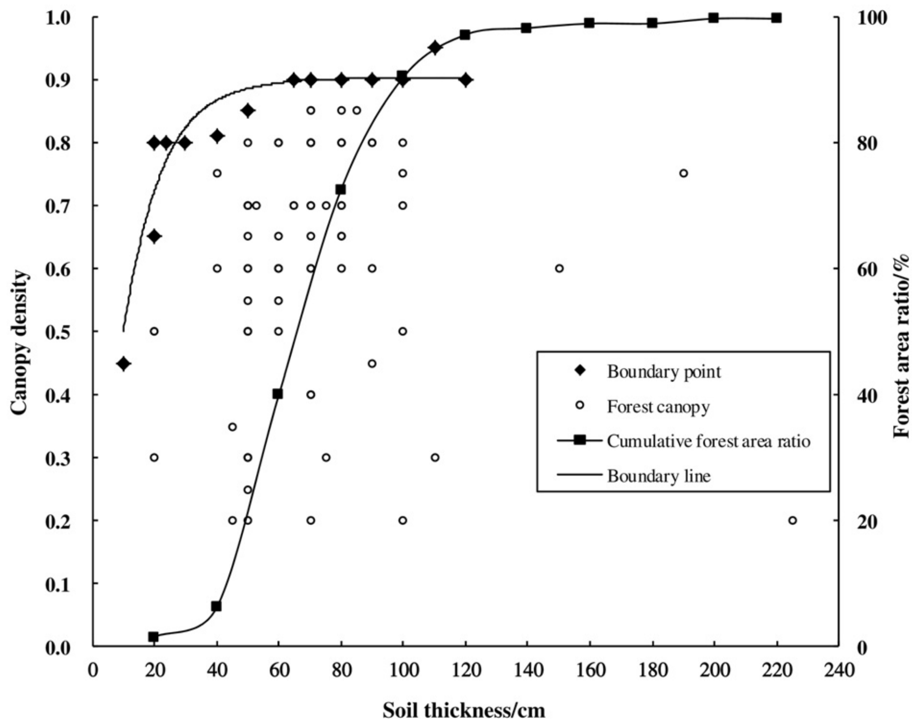

Fig. 4. Variation of canopy density of Qinghai spruce forests and the cumulative forest area ratio with soil thickness at the small watershed of Pailugou.

mean annual air temperature and precipitation are the most important and easily obtained factors; therefore, they are the most commonly used factors in studies (Eeley et al., 1999). With rising elevation, precipitation usually increases while air temperature decreases which produces lower evapotranspiration and thus increasing available water for plants (Coulter, 1967; Fu, 1983; Guo et al., 2013). This can largely explain the spatial distribution of forests with respect to elevation in high mountain areas within arid regions.

Compared with the main limitation of precipitation at the bottom tree line of arid high mountain areas, the upper tree line is mainly determined by the low air temperatures (Valmore, 1974). Studies in high-elevation areas of arid mountains have shown that the forest distribution and tree growth have been limited obviously by temperature or heat, such as low temperatures, short growing seasons, extreme minimum temperatures, and root development restriction by permafrost (Löve, 1970). It is therefore likely that the temperature increase will lead to an upward shift of forest distribution area. Kelly and Goulden (2008) compared surveys of plant cover along a 2314 m elevation gradient in Southern California's Santa Rosa Mountains, and found that the average elevation of the dominant plant species rose by about 65 m between the two surveys in 1977 and 2006–2007, mainly caused by the corresponding climate warming during this period. Similarly, high-mountain species in Europe will probably be forced to move to even higher altitudes (Hughes, 2000). A study performed on the future of the Alps also suggests that tree species will survive at higher altitudes (Theurillat and Guisan, 2001). Within the elevation range of 2500–

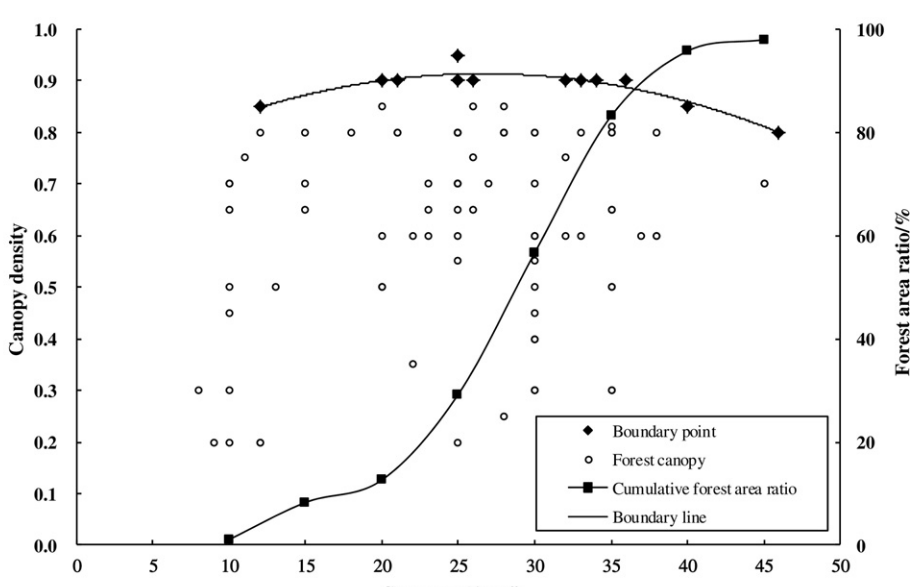

Fig. 5. Variation of forest canopy density and the cumulative forest area ratio with slope gradient at the small watershed of Pailugou.

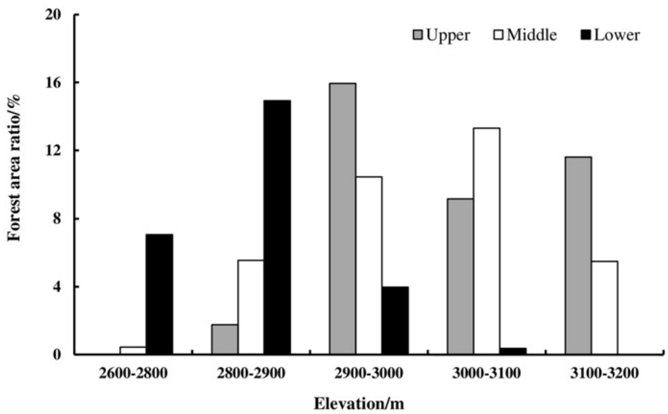

Fig. 6. The area ratio of Qinghai spruce forests at different slope positions and elevation ranges in the small watershed of Pailugou.

3800 m a.s.l. in Dayekou watershed, the decreasing rate of mean annual air temperature is 0.58 °C per 100 m increase in elevation (with the base mean annual air temperature of 1.6 °C at the elevation of 2580 m a.s.l.). This indicates that an increase of mean annual air temperature of 0.45 °C (the average increase per decade from 1980 to 2007 (Gao, 2015)) will shift the upper boundary of the potential distribution area and potential core distribution area of Qinghai spruce forests from 3325.8 to 3403.4 and from 3302.5 to 3380.1 m a.s.l., both with an elevation rise of 77.6 m. This predicted result is much more dramatic than the historical observed upward shifts of Qinghai spruce tree line elevation (5.7–13.6 m from 1907 to 1957 and 6.1–10.4 m from 1957 to 1980) affected by the warming climate (He et al., 2013), probably due to the fact that we have considered only the effect of temperature and not the time required for tree settlement and growth and other limiting factors.

The lower boundary of the forest distribution area in Dayekou is mainly limited by the annual precipitation. Based on the results of this study, Qinghai spruce forests are only located where the annual precipitation reaches 372.3 mm or more. Although there are scattered small pockets of Qinghai spruce forests beyond the lower boundary of the forest distribution area, they are not considered to be typical mountain forests as they live on water inputs besides precipitation, such as slope runoff, slope interflow, springs or stream water. Due to the prominent water limitation of mountain forests in arid regions, the increase/decrease of precipitation may lead to the downward/upward movement of the lower boundary (rear edge) of the forest distribution area. Brusca et al. (2013) have firstly documented the significant upward shifts of lower elevation range boundaries of montane plant species in Southwestern U.S. from 1964 to 2013, with a decreased mean annual precipitation and an increased mean annual temperature over the past 20 years.

The climate in the Qilian Mountains has shown a warm-wet transition since the 1980s, so the lower boundary of the potential distribution area and potential core distribution area of Qinghai spruce forests in the watershed of Dayekou will probably move downwards, to the elevation of 2495.0 and 2526.0 m a.s.l., if we simply link the lower boundary of forest distribution area with the mean annual precipitation and a 20 mm increase of annual precipitation at the elevation of 2580 m a.s.l. However, the temperature increase due to climate change can lead to an increase in evapotranspiration and drought frequency, which may counteract the effect of mean precipitation increase on the shift of the lower boundary of the forest distribution area. The ecological features, dynamics and conservation requirements of rear edge populations differ from those populations in other parts within the distribution range, and some commonly recommended conservation practices might therefore be of little use or even counterproductive (Hampe and Petit, 2005). So the lower boundary elevation of Qinghai spruce forests may not move downward consistent with the calculated result in this paper when just considering the limitation of annual precipitation. More studies are required to get a more precise and reliable quantitative prediction of the response of forest distribution area to climate change.

4.3. Influence of geographic factors on the spruce forest distribution

It is widely understood that the spatial distributions of vegetation species and shifts in distribution are not entirely determined by changes in climatic factors, but also influenced by other factors, such as soil, local topography and groundwater level (Iverson and Prasad, 1998; Talkkari and Hypén, 1996). The analyses in this study showed that the main geographic factors which limit the distribution of Qinghai spruce forests are elevation, slope aspect, soil thickness and slope position. While the soil thickness and slope position may more directly affect the distribution of spruce forests, the effect of elevation and slope aspect may largely be related with the change of climatic factors.

There was an obvious difference between the potential distribution area and potential core distribution area of Qinghai spruce forests in the widest slope aspect range, which were from −162.6° to 147.1° and −74.4° to 61.2° deviated from north in Dayekou watershed, respectively. This indicates that the slope aspect plays an important role in determining the distribution of Qinghai spruce forests within the suitable elevation range, because slope aspect can affect the incident radiation and therefore further affect the temperature, evapotranspiration and thus also the water budget and the available soil water for plants. Compared with sunny slopes, the shading from mountain slopes decreases the incident radiation and increases the available soil water and moisture condition on shady slopes (Olivero and Hix, 1998; Tian, 1996). This is a significant factor determining the spatial distribution of mountain forests. For instance, Douglas fir in eastern Washington always occupies the shady northern slopes and is entirely absent on the sunny southern slopes (Turesson, 1914). As a result of increasing annual precipitation with rising elevation, the slope aspect range of potential forest distribution area increases with rising elevation, until the elevation of 3080.2 and 3123.4 m a.s.l. for the potential distribution area and potential core distribution area, respectively. This is supported by the observation of Yuan (2015) that the growth of Qinghai spruce at the elevation of 3100 m a.s.l is not severely restricted by the changing climate.

Soil thickness can influence the existence and growth of forests, because it strongly affects the plant-available soil water amount, root development, tree recruitment (Dovčiak et al., 2003), and the buffering capacity against drought (Poff, 1996). Meerveld and McDonnell (2006) found that the spatial differences in soil thickness appear responsible for the observed spatial differences in species distribution. In this study, most Qinghai spruce forests (93.77% in area) grow on sites with a soil thickness of ≥40 cm. In the study of Yang (2001), it was also found that soil thickness above 40 cm is better for the growth of *Picea korainesis*. This indicates that soil thickness of ≥40 cm can store enough available water for Qinghai spruce forests to survive the dry periods. When the soil thickness is <40 cm within the lower elevation range of 2600–2900 m a.s.l., most spruce forests are located at the middle or lower slope position of shady slopes because the runoff from upslope can provide additional water input to meet the water demand of Qinghai spruce as a tree species with a shallow root system (Wu and Xing, 2015). Among the 29 units with soil thickness above 100 cm in Pailugou, 19 units are grassland located on slope aspects ranging from −60° to −160°, and only 3 units are covered by Qinghai spruce forests. This tells us that the limitation of soil thickness for forest distribution is much weaker than the limitation of slope aspect. This is supported by the study of Du (2009) which showed that *Picea balfouriana* on shady and semi-shady slopes with soil thicknesses of 45 and 38 cm grow better than the trees on the sunny and semi-sunny slopes with soil thicknesses of 62 and 55 cm.

Generally, gentle slopes provide better soil moisture and nutrients. In this study, the range of slope gradients that Qinghai spruce forests

occupied is as wide as 8–46°, and 91.73% of Qinghai spruce forests grow on moderate and steep slopes with a gradient of ≥15°, while 56.65% grow on the steepest slopes (>30°). This may be a result of land use competition, as gentle slopes (<15°) are preferred to be used as grassland for grazing. This may also be a result of past timber harvest. The forests in the Qilian Mountains were managed for timber production (mainly cutting) before the establishment of a national natural reserve in 1988. More timber harvest on sites with gentle slopes led to lower canopy density, and this has not been fully rehabilitated due to the very slow growth rate of Qinghai spruce. For example, the tree height and DBH of 10-years-old Qinghai spruce were recorded as 1.0 m and 1.6 mm, respectively; and tree height and radial growth do not accelerate until after the age of 20 years (Liu, 1992). However, it seems that the slope gradient is not a limiting factor for the distribution of Qinghai spruce forests, which is similar to the result of Niu et al. (2014).

The effect of slope position on the forest distribution is mainly caused by the downwards lateral movement of surface runoff and interflow in soil layers, which makes the upper slope drier and the lower slope wetter (Hewlett and Hibbert, 1963; Mowbray and Oosting, 1968). In this study, the Qinghai spruce forests are mainly distributed on lower-slopes in the elevation range of <2800 m a.s.l., and concentrated at the middle- and lower-slope positions within the elevation range of 2800–2900 m a.s.l., due to the relatively higher availability of soil water. The limitation of slope position to the spatial distribution of Qinghai spruce forests decreases with rising elevation. This can be explained by the improved soil moisture at upper- and middle-slopes due to the increased precipitation and decreased temperature and evapotranspiration with rising elevation. This study also indicates that the slope position does not play any limiting role for forest distribution when the elevation is above 2900 m a.s.l., where the precipitation is adequate. This finding is similar to some previous studies (Thor et al., 1969; Zhang et al., 2002). In this study, very few spatial units with a slope position of lower-slope exist in the small watershed of Pailugou in the elevation range above 3000 m a.s.l., due to the specific geographic condition, and probably also the limitations of the survey methods used. Further field investigation in other watersheds is necessary to better understand the effect of slope position on forest distribution.

4.4. Other factors that may influence the distribution of Qinghai spruce forests

In this study, the main factors influencing the spatial distribution of Qinghai spruce forests within mountain watersheds were analyzed and the thresholds of some of these factors were determined. The potential distribution area of Qinghai spruce forests and its quantitative expression using the main factors of elevation and slope aspect was determined. However, other features of geographic factors and climate change may create or enhance the spatial-temporal variation in soil-moisture that governs the distribution of Qinghai spruce forests (Pennington and Collins, 2007; Shi et al., 2007). Furthermore, under climate change the interactions between climate variables and other additional factors might become relevant (Ferguson and George, 2003). If the precipitation and temperature in this study are replaced by the climatic dryness or wetness indices, the prediction of the response of spatial distribution of Qinghai spruce forests to climate change should be more accurate. However, the calculation of the climatic dryness or wetness indices requires a number of meteorological factors, which are difficult to acquire, especially in mountain areas where these meteorological factors vary significantly with elevation, slope aspect and other factors.

The micro-topographic heterogeneity is assumed also to be responsible for the forest distribution patterns (Guisan and Theurillat, 2000). In this study, some scattered small pieces of Qinghai spruce forests beyond the lower boundary of the forest distribution area were found on lower slope positions or near streams in the Dayekou watershed. Consequently, micro-relief niches enable plant species to occur where they potentially would be missing from the viewpoint of meso-scale environments and, in turn, some are missing at fine scales where they potentially occur at broader scales (Erschbamer et al., 2001). Nevertheless, the study of Gottfried et al. (1998, 1999) showed that a considerable refinement of the DEM to even 1 m resolution does not substantially enhance the model accuracy. Thus the composition and diversity of alpine plant communities is strongly determined by specific disturbance regimes.

In addition to the effects of natural factors, enhanced anthropogenic activities in this area, such as land management, deforestation, and increasing and maintaining grassland for grazing, may also partly account for the observed distribution of Qinghai spruce forests. The human population in the Qilian Mountains has expanded dramatically in the last 50 years. Liu (2012) found that some suitable sites for forests were converted to other land uses, such as pastures or settlement. An extreme example is the Loess Plateau where Qinghai spruce had the maximum extent covering the whole Loess Plateau between 8000 and 6000 years B.C., but the increasing intensity of human activities since about 2000 years B.C. led to the disappearance of spruce forests (Zhou and Li, 2012). Nevertheless, migration by Qinghai spruce forests in response to past environmental changes have been observed, though it remains questionable whether forests have the potential to respond quickly enough to future climatic change.

Further work in tree physiology is required. Owing to the complexity of climate change and human intervention, the distribution-climate relationships of Qinghai spruce forests are not necessarily robust under future climate change scenarios. Integrated studies of ecology, hydrology and physiology, as well as further field investigations and controlled experiments, are needed to understand and quantify the impacts of individual factors and their interactions on the spatial distribution of Qinghai spruce forests under a changing climate and the influence of human activities.

Although the analyses of this study do not allow definitive conclusions on mechanisms underlying the adaptation of Qinghai spruce forests to climate change to be drawn, such analyses can elicit distribution patterns which might occur in future, taking certain assumptions on plant responses to climate change into account. They represent a long-term response trend rather than an expected real quick change of distributions. However, the research methods and qualitative conclusions of this study may provide a reference or guidance for studies on forest distribution in other dryland mountains.

5. Conclusions

The potential distribution area and potential core distribution area of Qinghai spruce forests in the Qilian Mountains of the dry northwest China were found to be within a borderline area, if considering only the limitations of elevation and slope aspect. The elevation ranges of the potential distribution area and the potential core distribution area of Qinghai spruce forests are 2603.4–3325.8 and 2635.5–3302.5 m a.s.l., respectively. The ranges of slope aspect borders of the two distribution areas vary with elevation, they are from −162.6° to 147.1° and −74.4° to 61.2° deviated from north at the elevation with the widest slope aspect range of forest distribution. The corresponding mean annual air temperature at the upper elevation boundary of these two distribution areas is −2.73 and −2.59 °C, while the mean annual precipitation at the lower elevation boundary is 372.3 and 378.1 mm, respectively. Using these thresholds and the elevation gradients of climatic factors, the change of upper and lower elevation boundaries of spruce forest distribution areas can be predicted for given climate change scenarios. However, this prediction can be greatly improved if more geographic factors (soil thickness and slope position) are included, mainly due to their effects on soil water availability for trees in drought periods. The most suitable soil thickness is ≥40 cm for all forests; while the suitable slope positions are lower-slope, lower- and

middle-slope, and anywhere for forests in the elevation range of <2800, 2800–2900 and >2900 m a.s.l. in the study region, respectively.

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Competing financial interests

The authors declare no competing financial interest.

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